Voyager 1 photopolarimeter experiment and the phase curve and surface microstructure of Ganymede

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Optical wavelength photometry used to determine the surface microstructure of Ganymede, shows that its surface is more porous than Callisto.

GANYMEDE, Jupiter's largest satellite, has a density of 1.9 g cm^{-3}, suggesting a bulk composition of about 50% water. Earth-based near-IR spectroscopic studies indicate that a half to two-thirds of its surface is covered with water ice[1]. Images of the satellite at a resolution of 2.5 km obtained by Voyager 1 cameras show an astonishing topography of cratered areas and grooved areas[2]. Most of the grooved terrain is a mosaic of systems of sinuous grooves and ridges. Radar echoes of Ganymede show a surprising reversal of the sense of reflected circular polarisation[3], indicating that the echoes arise principally from double reflections, and that the surface of Ganymede is therefore quite rough at the wavelength scale (13 cm). Optical wavelength photopolarimetry can reveal the surface characteristics of an atmosphereless object at a still finer scale, that is, its surface microstructure.

A detailed description of the Voyager photopolarimetry experiment has been published elsewhere[4]. The instrument was used as a single-wavelength photometer for whole-disk observations of Ganymede, made over a 3-day period, beginning 5.5 days before the closest approach to Jupiter. Figure 1 shows the brightness of Ganymede at 590 nm as a function of the range to the satellite. Each dot represents the average of 160, 320, 400, 320 and 160 individual raw data measurements, respectively, while the error bar denotes the standard deviation. The background count was essentially zero at such large distances from the radiation belts. As the range to the satellite decreased, its observed brightness did not increase with the inverse square of the distance (the smooth curve in Fig. 1). The instrument was seeing a smaller and smaller lit surface as the Sun–Ganymede–spacecraft angle (solar phase angle) was increasing. Ground-based photometry and Voyager 1 imaging have shown that the surface albedo of Ganymede is inhomogeneous, so that its integrated disk brightness varies with longitude.

It is not possible to separate the phase effect and the rotational effect using the Voyager 1 data alone. However, the rotational brightness variation of Ganymede has been observed from Earth through *UBV* bandpass filters[5]. Fortunately the spectral reflectance of Ganymede is rather flat in the wavelength interval common to the *V*-band (490–650 nm) and the bandpass of the Voyager photopolarimeter (570–610 nm) (see Fig. 2). Consequently we may correct for the rotational effect in our data (covering the longitude range 109°–264°) using published light curves, that is, Ganymede's nominal visual magnitude versus the rotational angle[5]. The magnitude of Ganymede as observed by the Voyager 1 photopolarimeter, corrected for rotational effect, and ground-based photometric observations[6] are shown in Fig. 3. These *V*-magnitudes have also been corrected for rotational effect. The data are limited to longitudes between 90° and 270° (the hemisphere facing away from Jupiter). The Voyager data have not been transformed into the *UBV* system but simply normalised to the ground-based observations.

With the extension to 33° phase angle, the shape of Ganymede's phase curve becomes more apparent. Satellite and asteroid phase curves are usually characterised by two parameters: the phase coefficient and the opposition effect. The slope of the straight line of best fit through data points between 6° and the maximum phase angle observable is called the phase coefficient. The magnitude actually observed at zero phase minus that extrapolated from the regression line just defined is called the opposition effect. Ganymede's phase coefficient and opposition effect derived from the data in Fig. 3 are 0.011 ± 0.001 mag per deg and 0.17 ± 0.03 mag, respectively. The error bars represent the statistical scatter in the data, and do not include systematic instrumental errors. There has been a long-term decrease of the instrument's sensitivity during the Voyager 1 mission. The decrease over the 3 days of this observational period is no more than 5%, based on consistency of Jupiter data. Correcting for such a decrease would lower the phase coefficient and increase the opposition effect. These changes are in directions that make the scientific conclusions stronger, as shown below. Other possible sources of systematic error were not checked immediately before Jupiter encounter. We suspect nonlinearity in the instrumental response at high count rates. We expect this effect was less at the count rates observed for Ganymede. However, we are encouraged by the fact that the reduced Voyager data in Fig. 3 are consistent with the phase curve expected from ground-based observations even though the raw data counts span a threefold range.

The derived phase coefficient of Ganymede is remarkably small. Asteroids typically have phase coefficients ranging from 0.020 to 0.055 mag per deg (ref. 7), while the Earth's Moon, Mercury and the martian satellites have values between 0.03 and 0.04 mag per deg (ref. 8). Only Europa[5,6] seems to have a phase coefficient smaller than that for Ganymede. The value for Ganymede approaches that of a Lambert sphere (a diffusely reflecting sphere, with a phase coefficient of 0.006 mag per deg at 20° phase angle).

Theoretical techniques for interpreting an observed phase curve to derive information on the surface of an atmosphereless object have been discussed by Veverka[9], Johnson and Matson[10], and others. The discussion below is modelled on that given by

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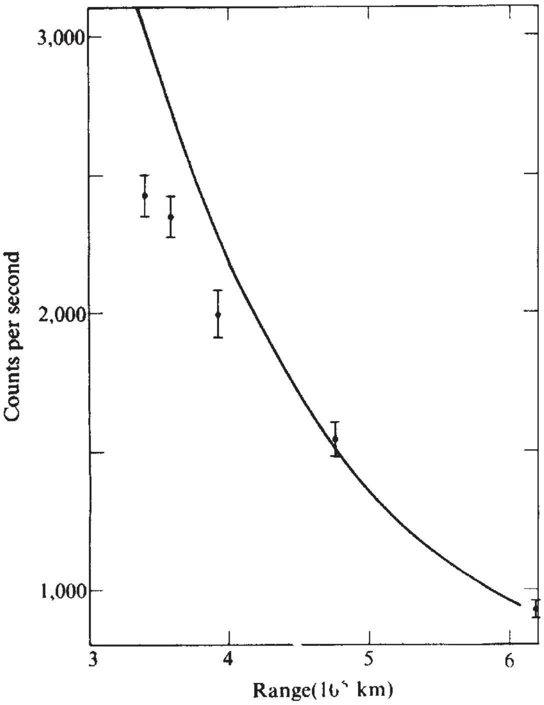

Fig. 1 Whole-disk brightness of Ganymede at 590 nm as a function of the distance between the satellite and the Voyager 1 photopolarimeter. Points are averages of many individual measurements (see text). Error bars are standard deviations. The smooth curve represents brightness variation according to the inverse square law.

Veverka. In essence there are three scales of surface roughness that determine the shape of an object's phase curve: the macroscopic or large-scale topography, the particulate or crystalline nature (microstructure), and small-scale texture intermediate to these two extremes. Shadowing by topographical features is of major importance at all but the smallest phase angles. The greater the large-scale roughness, the greater will be the phase coefficient. The albedo and scattering phase function of the individual particles or crystals are determined by their size, shape, and complex refractive index. Multiple scattering among the particles is generally important, except for the very darkest materials. The greater the particle albedo, the greater the multiple scattering, and the less will be the phase coefficient. For transparent or translucent particles, diffuse transmission and reflection are also involved. The intermediate scale of roughness, the 'texture' of the surface, is determined mostly by the packing characteristics of the particles. The porosity of a surface strongly influences the phase curve at small phase angles.

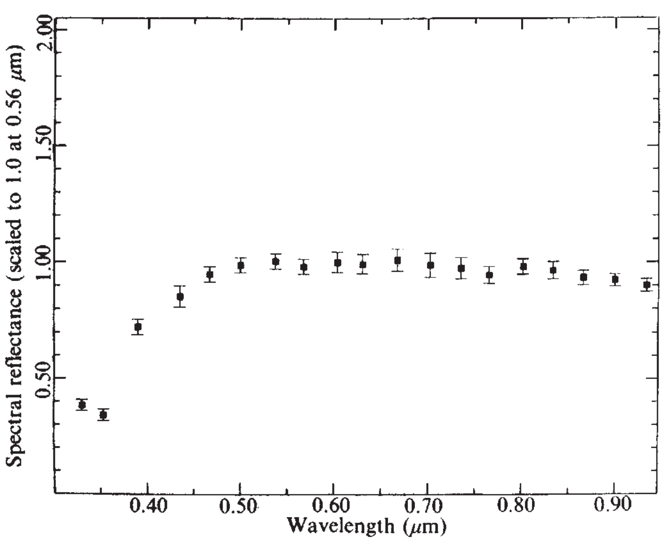

Fig. 2 The relative spectral reflectance of Ganymede as observed from the 224-cm telescope on Mauna Kea Observatory on 28 December 1978. Error bars represent standard deviations of different measurements taken during the same night.

Modelling of scattering by surfaces is primitive; it is not yet possible to derive surface parameters from observed phase curves only. However, if information on two of the three scales of roughness is available one may set limits on the third. The Hapke–Irvine model for approximating the opposition effect of a dark surface is a case of such an analysis. This model applies to dark particles, for which multiple scattering may be neglected, and to very small phase angles, so that shadowing by large-scale topographic features is not important. With these simplifying assumptions the opposition effect of such a layer is determined

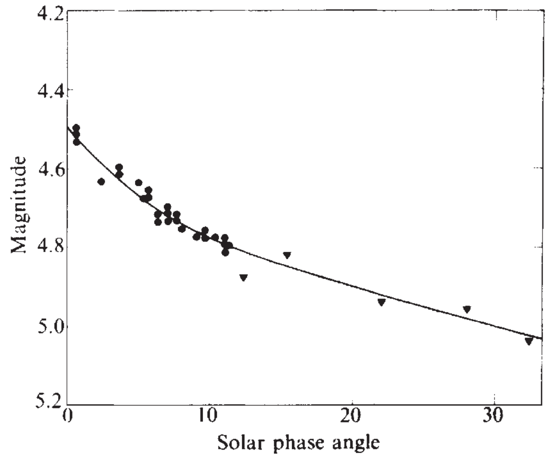

Fig. 3 The phase curve of Ganymede for the hemisphere facing away from Jupiter (longitudes between 90° and 270°). Rotational brightness variations have been corrected for. The Voyager data (▼) are normalised to the ground-based observations (●) of Millis and Thompson[6].

largely by the packing characteristics, described by the compaction parameter.

$$D = \frac{3}{4\pi} \times \frac{\rho}{\rho_0}$$

where ρ is the density of a macroscopic volume element and ρ_0 is the density of a single particle. The Hapke–Irvine model seems to fit available observations of dark surfaces and seems useful in establishing relative values of D. Veverka[9] used this model to compute opposition surges for a variety of compaction parameters. A surface with $D \sim 0.13$ exhibits no opposition effect. As D decreases the surface becomes more porous, and the opposition effect develops. For the leading (trailing) side of Callisto, which has an opposition surge of 0.25 mag (0.13 mag), D would be approximately 0.025 (0.04). The surface material on Callisto thus seems to be rough and porous. All other factors being equal a larger opposition effect means a more porous surface.

Although it is tempting to use the Hapke–Irvine model in analysing the phase curve of Ganymede, we must bear in mind that this model is valid only for dark surfaces like that of the moon (visual albedo 0.12) and Callisto (0.17). The visual albedo of Ganymede, 0.43, is too high for the simplifying assumptions to be valid. However, the topographies of Callisto and Ganymede seem to be similarly rough (Callisto is more heavily cratered but Ganymede is extensively grooved), and the degrees of roughness of the two satellites at 13 cm scale are similar. (In contrast to Ganymede and Callisto the small-scale texture of Io appears to be smooth. 13-cm roughness estimates are from radar observations by Pettengill.[3]) The opposition effect of Ganymede (0.17 mag) is slightly larger than that of the trailing side of Callisto (0.13 mag). Now if the topographical and 13-cm scale degrees of roughness of the two satellites are similar and their opposition surges are nearly the same, but Ganymede is 2.5 times brighter than Callisto, then it seems probable that the surface of Ganymede is the more porous of the two. If all three scales of roughness were the same, Ganymede would have a smaller opposition effect because, having brighter surface particles, multiple scattering of light would tend to wash out the effects of shadowing. Increased shadowing effects from a more porous surface on Ganymede compensate for the multiple scattering reduction of the opposition effect.

We arrive at a similar conclusion by comparing the phase coefficients of Ganymede and Callisto. Callisto's phase coefficient (0.025 mag per deg) is more than twice as large as that of Ganymede (0.011 mag per deg). Assuming that the large and intermediate scale roughnesses of the satellites are similar their phase coefficients should be the same if their albedos were the same. The greater albedo of Ganymede results from greater single particle albedo, which implies more multiple scattering, therefore a lower phase coefficient. A porous surface layer is necessary to effect the multiple scattering. Ground-based polarisation studies of Ganymede led to a similar conclusion[11]. Thus, within the limitations of our simplifying assumptions, we conclude that the surface layer of Ganymede (the hemisphere facing away from Jupiter) is porous, and more so than for Gallisto (the trailing side). In contrast to Ganymede, the transient south polar cap of Mars has a quasi-specular surface[12]. The difference could be due to annual resurfacing on Mars, while micrometeoroids continuously roughen the surface of Ganymede.

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1. Pollack, J. B., Witteborn, F. C., Erickson, E. F., Strecker, D. W., Baldwin, B. J. & Bunch, T. E. *Icarus* **36**, 271–303 (1978).
2. Smith, B. A. *et al. Science* **204**, 951–972 (1979).
3. Pettengill, G. B. *A. Rev. Astr. Astrophys.* **16**, 265–292 (1978).
4. Lillie, C. F., Hord, C. W., Pang, K., Coffeen, D. L. & Hansen, J. E. *Space Sci. Rev.* **21**, 159–182 (1977).
5. Morrison, D. & Morrison, N. in *Planetary Satellites* (ed. Burns, J. A.) 363–378 (University of Arizona Press. 1977).
6. Millis, R. L. & Thompson, D. T. *Icarus* **26**, 408–419 (1975).
7. Bowell, E. *Bull. Am. Astr. Soc.* **8**, 460 (1976).
8. Pang, K. D., Rhoads, J. W., Lane, A. L. & Ajello, J. M. *Nature* (submitted).
9. Veverka, J. in *Planetary Satellites* (ed. Burns, J. A.) 171–209 (University of Arizona Press, 1977).
10. Johnson, T. V. & Matson, D. L. *Bull. Am. astr. Soc.* **10**, 597 (1978).
11. Veverka, J. in *Planetary Satellites* (ed. Burns, J. A.) 210–231 (University of Arizona Press, 1977).
12. Pang, K. & Hord, C. W. *Icarus* **15**, 443–453 (1971).